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1. Your reference	519GB
2. Patent application number *(The Patent Office will fill in this part)*	0404829.4 04 MAR 2004
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	Renishaw plc New Mills Wotton-under-Edge Gloucestershire, GL12 8JR
Patents ADP number *(if you know it)*	2691002
If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4. Title of the invention	Optical Readhead
5. Name of your agent *(if you have one)*	E C Leland et al
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Renishaw plc Patent Department New Mills Wotton-under-Edge Gloucestershire, GL12 8JR
Patents ADP number *(if you know it)*	~~26196~~ 2691003

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11. I/We request the grant of a patent on the basis of this application.

Signature [signature] Date 04.03.2004

AGENT FOR THE APPLICANT

12. Name and daytime telephone number of person to contact in the United Kingdom — A ILES 01453 524524

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OPTICAL READHEAD

The present invention relates to an optical readhead for measuring changes in the lateral position of interference fringes. Such a readhead may be used, for example, in interferometry.

In an interferometry apparatus, two coherent beams are interfered together to form a periodic light pattern in the form of interference fringes at a detection unit, which contains electronics, such as photodiodes and amplifiers etc.

It would be advantageous to have a readhead in which no electronics are required. This would allow the size of the readhead to be reduced. Furthermore, if the readhead does not have electronics the problem of electronic noise from other components (such as motors) is eliminated.

The electronics in the detection unit are a heat source which can cause measurement error due to expansion of parts of the apparatus. Thus it is desirable to remove this heat source.

The present invention provides an optical readhead for measuring changes in the lateral position of a periodic light pattern comprising an optical element configured such that when the periodic light pattern is incident on the optical element a plurality of beams are produced each beam having a different phase and a different direction and a plurality of detectors positioned so that each detector detects the intensity of a different beam.

The optical element may comprise a diffractive optical element (DOE).

The optical element may have a profiled surface, such that the plurality of beams are produced by refraction at the profiled surface.

The optical element may comprise a plurality of segments, wherein light incident on each segment is diffracted into a different diffraction direction, thus producing the plurality of beams.

Preferably the intensities of the beams vary as the periodic light pattern translates. In one embodiment four beams are produced, wherein the intensities of the four beams vary in quadrature as the fringes translate. In another embodiment three beams are produced.

The periodic light pattern may comprise interference fringes.

The detectors may be adjacent to the optical element. Alternatively the detectors may be remote from the optical element, for example optical fibres, may be used to channel the beams to the remotely located detectors.

At least one lens may be provided to focus light beams into the optical fibres.

Embodiments of the invention will now be described by way of example and with reference to the accompanying drawings in which:

Fig 1 is a representation of the readhead of the present invention;

Fig 2 illustrates the phase difference of the four resultant beams produced in the apparatus shown in Fig 1;

Fig 3 illustrates the cosine fringes on a DOE to provide four beams;

Fig 4 illustrates the convolution of the complex amplitude of the grating $\Omega grating(\omega)$ and complex amplitude of the fringes $\Omega fringes(\omega)$ to produce the output complex amplitude $\Omega out(\omega)$;

Fig 5a illustrates the real and imaginary parts of the grating amplitude for a first solution;

Fig 5b illustrates the phase and intensity of the grating for the first solution;

Fig 5c illustrates the output intensity against angular displacement of the four resulting beams for the first solution;

Fig 6a illustrates the real and imaginary parts of the grating amplitude for a second solution;

Fig 6b illustrates the phase and intensity of the grating for the second solution;

Fig 6c illustrates the output intensity against angular displacement of the four resulting beams for the second solution;

Fig 7a illustrates the real and imaginary parts of the grating amplitude for a third solution;

Fig 7b illustrates the phase and intensity of the grating for the third solution;

Fig 7c illustrates the output intensity against angular displacement of the four resulting beams for the third solution;

Fig 8 illustrates the convolution of the complex amplitude of the grating $\Omega grating(\omega)$ and the complex

amplitude of the fringes Ωfringes(ω) to produce an output complex amplitude Ωout(ω) for a three phase grating.

Fig 9a illustrates the real and imaginary parts of the grating amplitude for a 3-phase splitting grating;

Fig 9b illustrates the phase and intensity of the grating for a 3-phase splitting grating;

Fig 9c illustrates the output intensity against angular displacement of the four resulting beams for a 3-phase splitting grating;

Fig 10 illustrates an optical element having a profiled upper surface;

Fig 11 illustrates the optical element of Fig 10 showing the deflected light paths;

Fig 12 illustrates a perspective view of an optical element including blazed gratings;

Fig 13 is a plan view of the optical element of Fig 12;

Fig 14 is a side view of the optical element of Fig 12;

Fig 15 is a schematic illustration of a birefringent optical element having a profiled upper surface; and

Fig 16 illustrates light passing through the optical element of Figs 12-14 being focused into optical fibres by a Fresnel zone plate.

The invention will now be described with reference to Fig 1. A readhead 10 comprises a diffractive optical element (DOE) 12, a lens 14 and four detectors 16,18,20,22. A periodic light pattern 24 comprising cosine fringes formed at the readhead 10 by the interference of two coherent light beams 26,28. Such a periodic light pattern may be formed for example in

interferometry apparatus.
When the readhead 10 is illuminated by the cosine fringes four beams 30,32,34,36 are formed which are focused by lens 14 onto detectors 16,18,20,22. Alternatively four individual lenses could be used. The four beams are 90° out of phase and thus the intensities detected at the detectors vary in quadrature as the cosine fringes are translated across the readhead.

Fig 2 illustrates the intensity variation at the detectors 16,18,20,22 over time as the cosine fringes are moved laterally relative to the readhead 10. It can be seen that the intensities of each detector 16,18,20,22 vary cyclically and are 90° out of phase with one another.

The invention is not restricted to producing four light beams. For example the DOE may be designed to create three beams which are $\pi/2$ or $4\pi/3$ out of phase depending upon the design. The output of the detectors may be combined to generate quadrature signals which may be used to interpolate the magnitude and direction of relative movement between the fringes and the periodic light pattern. The method of combining outputs from three detectors to generate such quadrature signals is disclosed in our earlier published International Patent Application WO87/07944.

The mathematical specification of the DOE may be calculated as follows with reference to Figs 3-7.

Fig 3 shows cosine fringes 24 incident on a DOE 40 to provide four beams a,b,c,d which vary in intensity

I_1, I_2, I_3, I_4 and quadrature as the cosine fringes are translated relative to the readhead. The cosine fringes may be described by the equation:

$$Ufringes(x) = \cos\frac{2\pi(x - \Delta x)}{p}$$

where x is the linear displacement; Δx is the change in linear displacement; and p is the periodicity of the complex amplitude field produced by the interference of the two incident beams. The periodicity of the intensity interference pattern is p/2.

The output complex amplitude Ωout(ω) of the DOE is given by the Fourier transform of the product of the cosine fringes (Ufringes (x)) and the DOE as shown below. Output coordinates are

$$\underline{x} = \underline{\omega}.\lambda z$$

where λ is the wavelength of the incident light, ω is the spatial angular frequency of the co-ordinate system, and z is the propagation distance.

$$\begin{aligned} \Omega out(\omega) &= Ft[Ufringes(x).Ugrating(x)] \\ &= Convolution[\ Ft[Ufringes(x),\ Ft[Ugrating(x)] \\ &= Convolution[\ \Omega fringes(\omega),\ \Omega grating(\omega)\ ] \end{aligned}$$

where Ft is the Fourier Transform.

The form of the complex amplitude of the grating Ωgrating(ω) must be such that when convolved with the complex amplitude of the fringes Ωfringes(ω) it produces at least four beams. Furthermore as the

intensity of the four beams is required to vary in quadrature with Δx, it is necessary for the complex amplitude of each beam to consist of at least two components so that the required phase relationship can be imposed. (Single component beams are not suitable as they would have constant intensity.) A possible solution is illustrated in Fig 4. Fig 4 illustrates the convolution of $\Omega grating(\omega)$ and $\Omega fringes(\omega)$ to produce $\Omega out(\omega)$. A-E are complex numbers and

$$\phi=2\pi\Delta x/p$$

The output intensity is given by the square of the modulus of the output amplitude. The intensities of the four beams can then be equated to the required quadrature signals:

$$I_n(\Delta x) = 1 + q \operatorname{Cos}(2\phi + n\pi/2)$$

where q is the AC modulation with a DC level of unity.

Let I_1 be the modulus squared of the complex amplitude of the first output beam resulting from the combination of the incident beams and the property of the DOE, then

$$I_1 = |\tfrac{1}{2}(Ae^{-i\phi}+Be^{+i\phi})|^2$$

$$= \tfrac{1}{4}(Ae^{-i\phi}+Be^{i\phi})(A^*e^{i\phi}+Be^{-i\phi})$$

This can be related to the required modulated intensity terms by

$$I_1 = \tfrac{1}{4}(|A|^2+|B|^2+AB^*e^{-2i\phi}+A^*Be^{2i\phi})$$
$$=1 + q\mathrm{Cos}2\phi = 1+\frac{q}{2}(e^{2i\phi}+e^{-2i\phi})$$

Similarly

$$I_2 = \tfrac{1}{4}(|B|^2+|C|^2+BC^*e^{-2i\phi}+B^*Ce^{2i\phi})$$
$$= 1+q\mathrm{Cos}(2\phi+\pi/2) = 1+\frac{q}{2}(e^{i(2\phi-\pi/2)}+e^{-i(2\phi-\pi/2)})$$
$$I_3 = \tfrac{1}{4}(|C|^2+|D|^2+CD^*e^{-2i\phi}+C^*De^{2i\phi})$$
$$= 1+q\mathrm{Cos}(2\phi-\pi) = 1+\frac{q}{2}(e^{i(2\phi-\pi)}+e^{-i(2\phi-\pi)})$$
$$I_4 = \tfrac{1}{4}(|D|^2+|E|^2+DE^*e^{-2i\phi}+D^*Ee^{2i\phi})$$
$$= 1+q\mathrm{Cos}(2\phi-3\pi/2) = 1+\frac{q}{2}(e^{i(2\phi-3\pi/2)}+e^{-i(2\phi-3\pi/2)})$$

Thus

$$\tfrac{1}{4}AB^*=\frac{q}{2} \text{ and } \tfrac{1}{4}A^*B=\frac{q}{2}$$

$$\tfrac{1}{4}BC^*=\frac{q}{2}e^{+i\pi/2} \text{ and } \tfrac{1}{4}B^*C=\frac{q}{2}e^{-i\pi/2}$$

$$\tfrac{1}{4}CD^*=\frac{q}{2}e^{+i\pi} \text{ and } \tfrac{1}{4}C^*D=\frac{q}{2}e^{-i\pi}$$

$$\tfrac{1}{4}DE^*=\frac{q}{2}e^{+i3\pi/2} \text{ and } \tfrac{1}{4}D^*E=\frac{q}{2}e^{-i3\pi/2}.$$

The equations on the right hand side are just complex conjugates of the left hand side ones and can be neglected.

Starting with an arbitrary A value.

$$B = \left(\frac{2q}{A}\right)^*$$

$$C = ((2q/B)e^{i\pi/2})^*$$

$D = ((2q/C)e^{i\pi})^*$

$E = ((2q/D)e^{i3\pi/2})^*$

Now let A=1, q=¼, then the values of A-E are

A = 1
B = 1
C = -i
D =+i
E =-1

This system is illustrated in Figures 5. Fig 5a shows the real and imaginary parts of the grating amplitude against displacement x, Fig 5b shows the phase and intensity of the grating against displacement x and Fig 5c shows the output intensity in the spatial frequency co-ordinate system (ω).

Two alternative solutions are also possible, which differ only in the order of the phases. These are illustrated in Figs 6 and 7.

Fig 6a shows the real and imaginary parts of the grating amplitude against displacement x, Fig 6b shows phase and intensity of the grating against displacement x and Fig 6c shows the intensity in the spatial frequency co-ordinate system (ω) for the four resulting beams a,b,c,d for the values of A-E below:

A = I

$B = e^{i0\pi/2}/A$

$C = e^{i1\pi/2} / B$

$D = e^{i3\pi/2} / C$

$E = e^{i2\pi/2} / D$

Thus

$A = 1$ $B = 1$ $C = i$ $D = -1$ $E = 1$

Fig 7a shows the real and imaginary parts of the grating amplitude against displacement x, Fig 7b shows phase and intensity of the grating against displacement x and Fig 7c shows the intensity in the spatial frequency co-ordinate system (ω) for the four resulting beams a,b,c,d for the values of A-E below:

$A = 1$

$B = e^{i0\pi/2} / A$

$C = e^{i2\pi/2} / B$

$D = e^{i1\pi/2} / C$

$E = e^{i3\pi/2} / D$

Thus

$A = 1$ $B = 1$ $C = -1$ $D = -i$ $E = 1$

It is also possible to use the D.O.E. to produce three resultant beams. A possible solution is illustrated in

Fig 8 and the equations below.

$$A = 1$$

$$B = e^{-i.1.\pi/2}/A$$

$$C = e^{i.0.\pi/2}/B$$

$$D = e^{i.1.\pi/2}/C$$

$A = 1$ $B = -i$ $C = i$ $D = 1$

Fig 9a illustrates the real and imaginary parts of the grating amplitude for a three phase splitter grating, Fig 9b illustrates the phase and intensity of the three phase splitter grating and Fig 9c illustrates the output intensity against angular displacement (ω) for the three output beams a,b.c.

The above solutions are specific analytical solutions. Numerical optimisation of the DOE will typically use a computer and produce designs that may not be of the above form but may make the DOE easier to make and use.

An alternative optical element for forming a plurality of light beams from an incident cosine wave will now be described with reference to figs 10 and 11.

Fig 10 illustrates an optical element 50 comprising a transparent, eg glass, element 52 with a profile 54 on one surface comprising a repeating pattern of three surfaces 56, 58, 60 of equal distance angled at for example 120° from one another.

This profile may be formed from a saw tooth profile, in which the top third is removed (for example, by polishing).

A periodic pattern comprising cosine fringes 62 is formed at the optical element 50 by the interference of two coherent light beams 64, 66. Fig 10 shows cosine fringes 62 incident on the optical element 50. Light incident on the profiled optical element is refracted in three different directions 68, 70, 72 by the three angled surfaces, as shown in fig 11. The period of the optical element 74 is equal to the period of the cosine fringes 76, resulting in the three resultant light beams having different phases of 0°, +120° and -120°.

Detectors (not shown) are provided to detect the three resultant light beams 68,70,72. Alternatively, optical fibres may be provided to couple the three resultant light beams to their respective remote detectors.

In a reverse arrangement, the coherent light beams 64,66 are incident on the plane face of the optical element, so that the light travels across the profiled glass/air boundary from the glass side. In this arrangement the angle of incidence of the light beams 64,66 will be greater than the arrangement illustrated in Figs 10 and 11 to produce a fringe pitch in the glass which is equal to the period of the profiled surface.

The incident beams which interfere with each other to produce an interference patterns do not have to be at an angle to one another. Fig 15 illustrates an

embodiment in which the optical element 150 is made from a birefringent material which has a polaroid material 151 coated onto its profiled surface 158. Two parallel beams 164,166 which are orthogonally polarised are incident on the optical element, and are refracted by differing degrees by the birefringent material. The beams are thus no longer parallel when they meet and interfere at the polarising coating to form an interference pattern. The interference pattern interacts with the profiled surface as previously described with reference to Figs 10 and 11.

Another type of profiled optical element will now be described with reference to figs 12-14. In this embodiment, the optical element 80 comprises a transparent element 82, eg glass, with a profiled surface 84.

The profiled surface 84 of the optical element is divided into a repeating pattern of segments 88,90,92, the pattern of segments extending parallel with the direction of the light fringes 86. Figs 12 and 13 show the repeating pattern of segments. Fig 12 is a perspective view of the optical element and fig 13 is a plan view. Each repeatable section of the pattern comprises a first segments 88 in which there is no structure, a second segment 90 in which there is a blazed grating extending in a first direction (shown by arrow A in Fig 13) and a third segment 92 in which there is a blazed grating extending in a second direction (shown by arrow B in Fig 13).

Light incident on the different segments of the profiled surface of the optical element is diffracted

into different directions. Light incident on the first segment without any structure passes straight through the optical element (i.e. 0^{th} order of diffraction). Light incident on the second and third segments is refracted at different angles.

Fig 14 is an end view of the optical element of figs 12 and 13. Light 94 incident on the top face of the optical element 80 passes straight through segment 88 (without structure), is diffracted in a first direction passing through the segment 90 (with a blazed grating in a first direction) and is diffracted in a second direction passing through the segment 92 (with a blazed grating in a second direction). The light beams produced by the three segments are focussed by lens 96 into three light spots 98,100,102 which are transverse to the direction of the repeating pattern of segments. As light incident on each of the segments 88,90,92 each relates to a different part of the cosine fringes, the three light spots will each have different phases, i.e. 0°, +/-120°.

Use of a blazed grating has the advantage that the lens 96 may be incorporated into the optical element 80 by superimposing a Fresnel zone plate onto the blazed grating, thus reducing the total size of the system.

Fig 16 illustrates part of the Fresnel zone plate which focuses light into the optical fibres. The zone plate comprises sets of sections A,B,C with each section of a given set focusing the light to a given focal point. Difference sets of sections focus light to different focal points. The Fresnel zone plate may be configured so that the focal points are arranged either parallel

or transverse to the plane of the optical fibre. Fig 16 shows light diffracted by a first set of segments 88 of the blazed grating being focused into a first optical fibre 170, light diffracted by a second set of segments 90 of the blazed grating being focused into a second optical fibre 172 and light diffracted by a third set of segments 192 of the blazed grating being focused into a third optical fibre 174.

If heat from the electronics is acceptable then photodetectors could be used instead of the optical fibres. Here the photodetectors could be separate, or housed within the same unit or they may even have a common substrate as in quadcells or linear arrays.

Although Figs 10-16 illustrate transmissive systems, a reflective optical element may also be used in the invention.

All of the above embodiments provide alternatives for an opto-electronic grating, thus providing a readhead in which no electronics are required. Furthermore, as the detectors may be provided remotely from the readhead (i.e. by use of optical fibres), the size of the readhead may be greatly reduced.

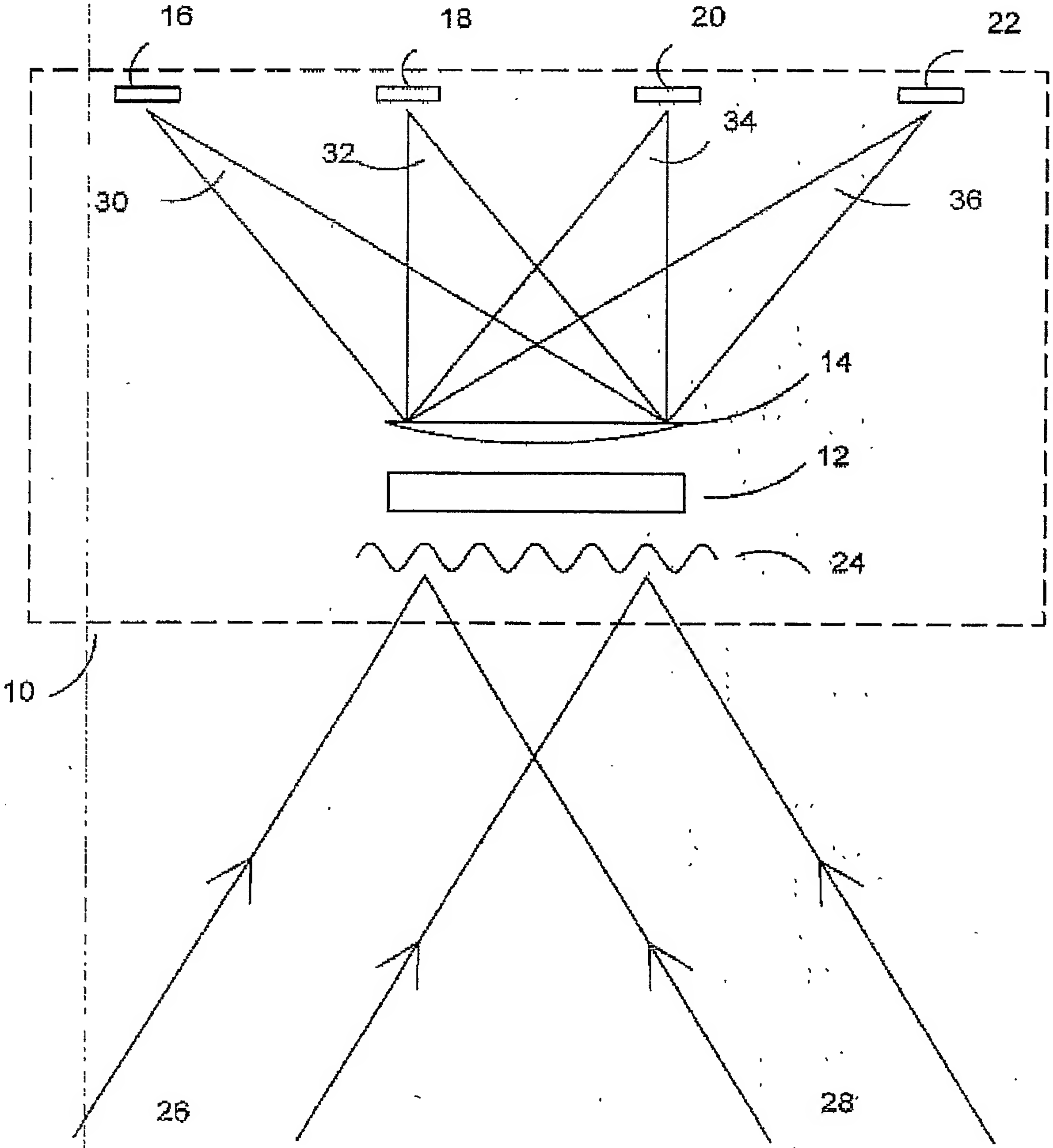


Fig 1

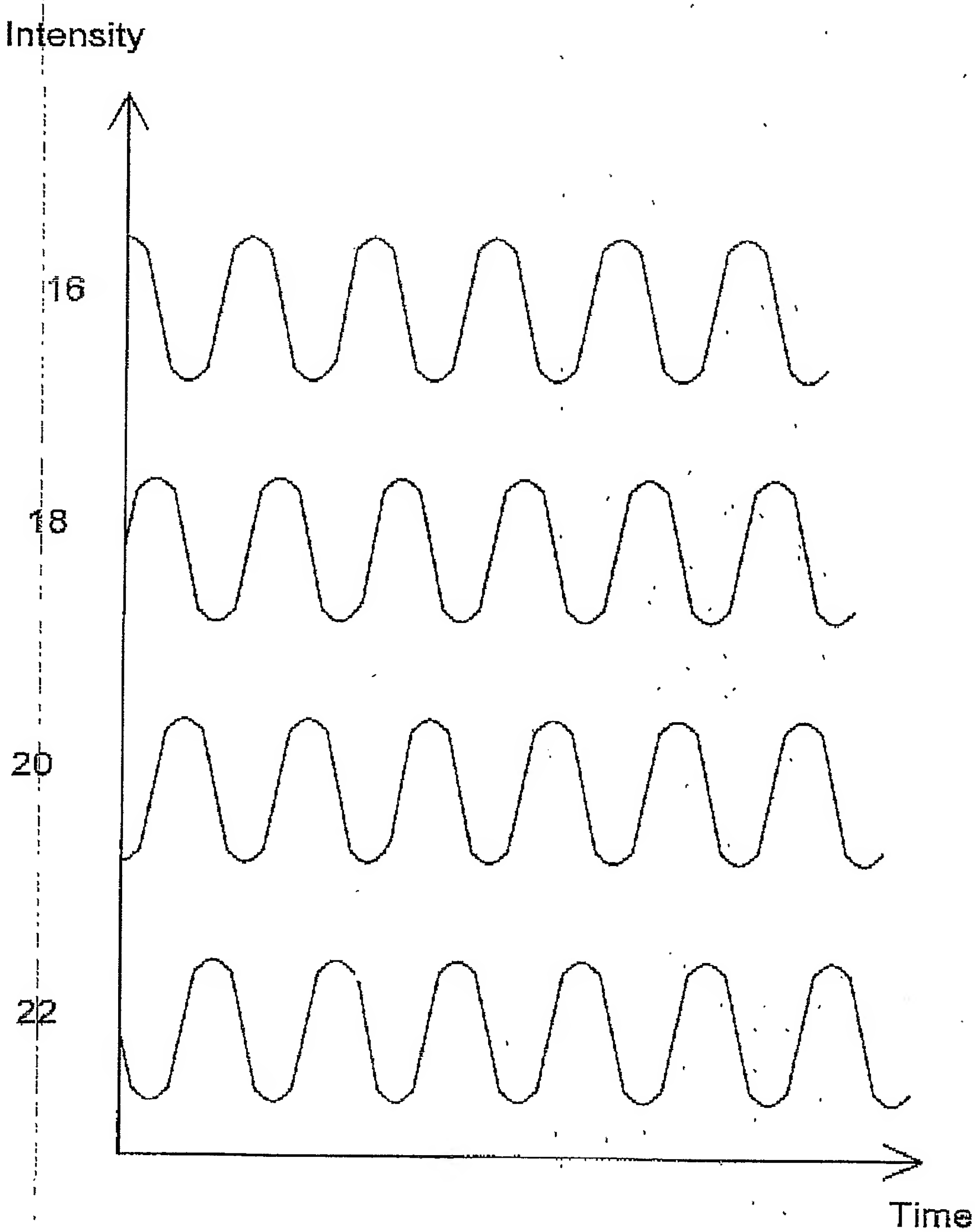


Fig 2

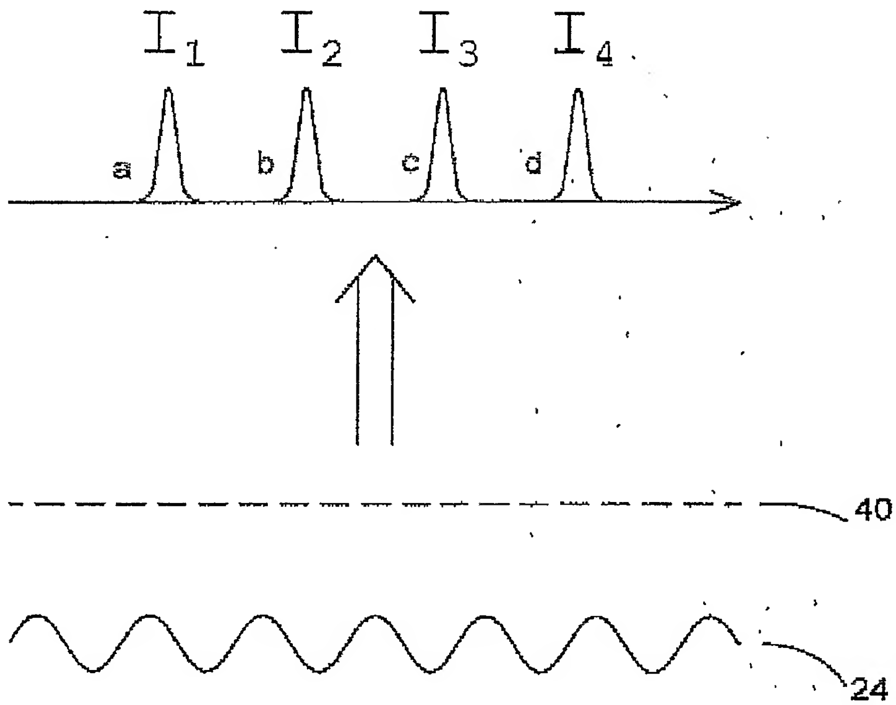
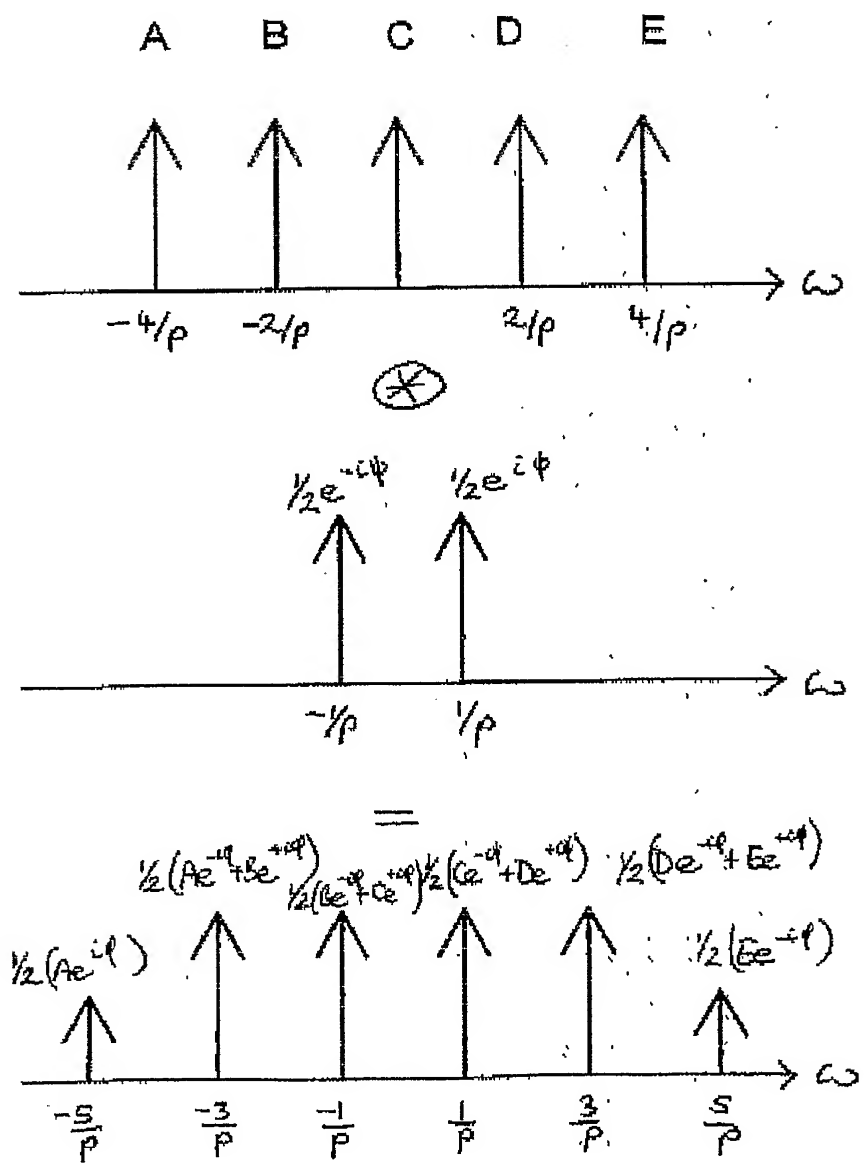


Fig 3


A
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ω
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4/p
½e^{-iφ}
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−1/p
1/p
=
½(Ae^{iφ})
½(Ae^{-iφ}+Be^{+iφ})
½(Be^{-iφ}+Ce^{+iφ})
½(Ce^{-iφ}+De^{+iφ})
½(De^{-iφ}+Ee^{+iφ})
½(Ee^{-iφ})
ω
−5/p
−3/p
−1/p
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3/p
5/p

Fig 4

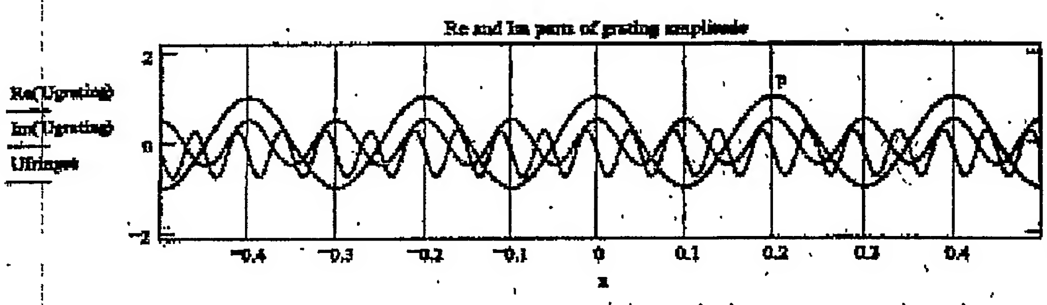

Fig 5a

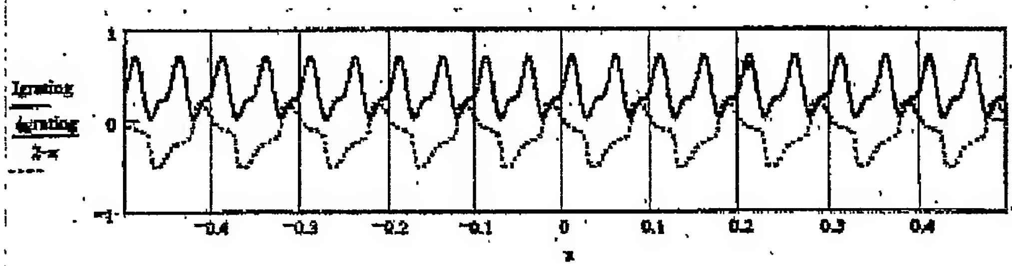

Fig 5b

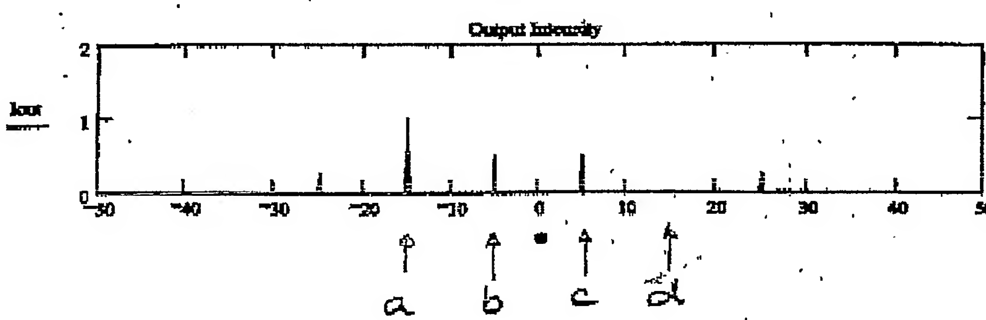

Fig 5c

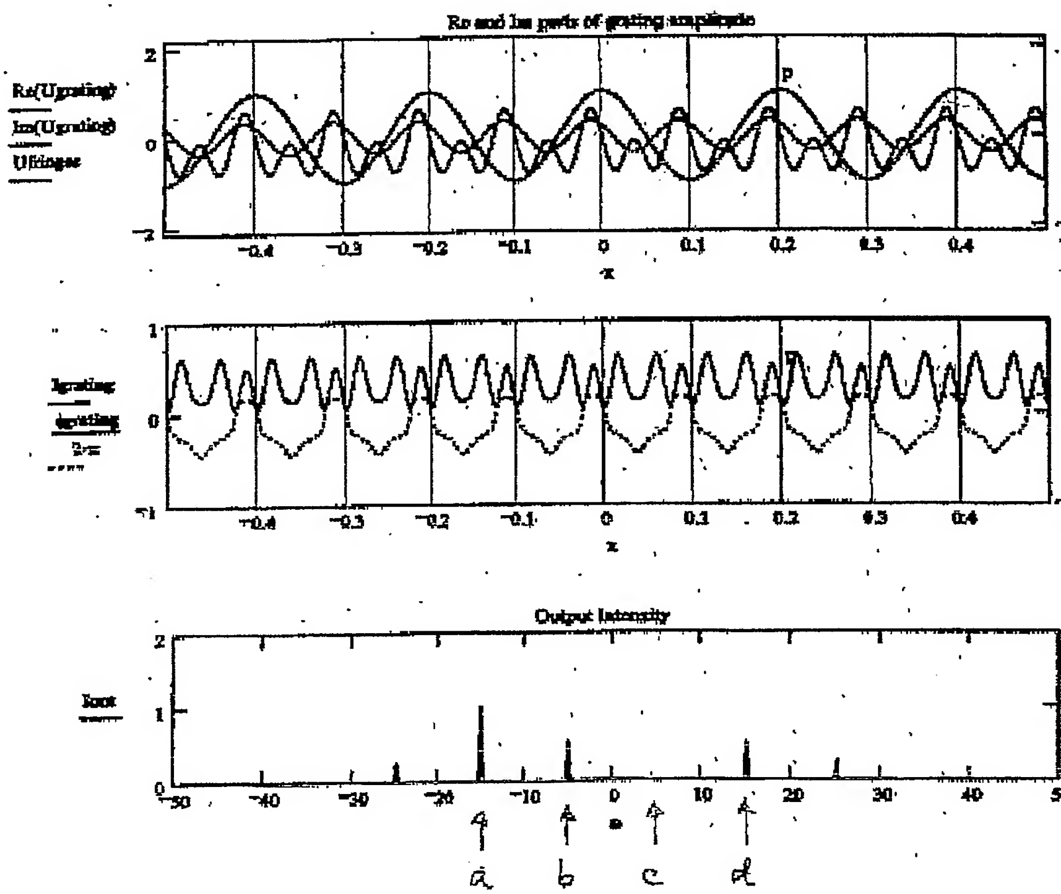

Fig 6A

Fig 6B

Fig 6C

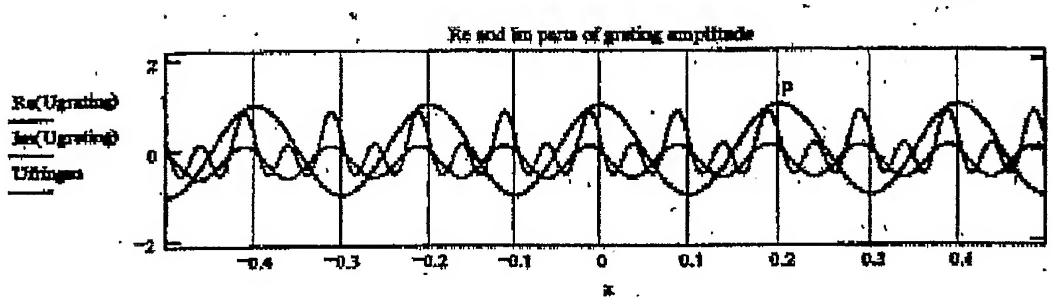

Fig 7a

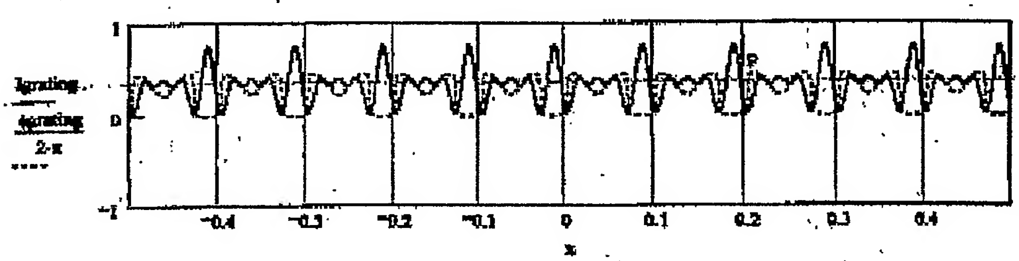

Fig 7b

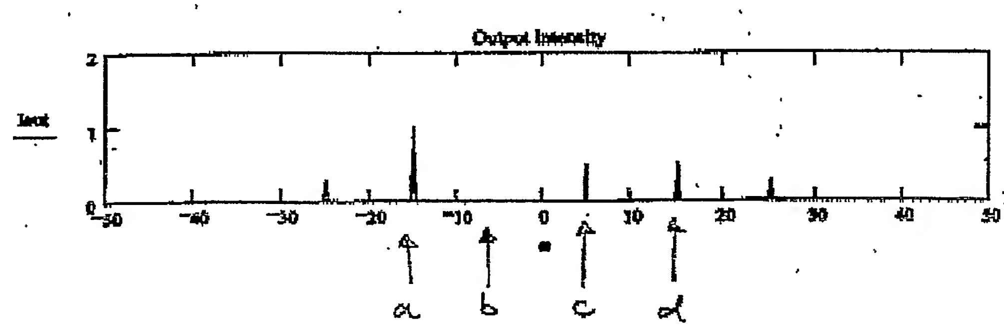

Fig 7c

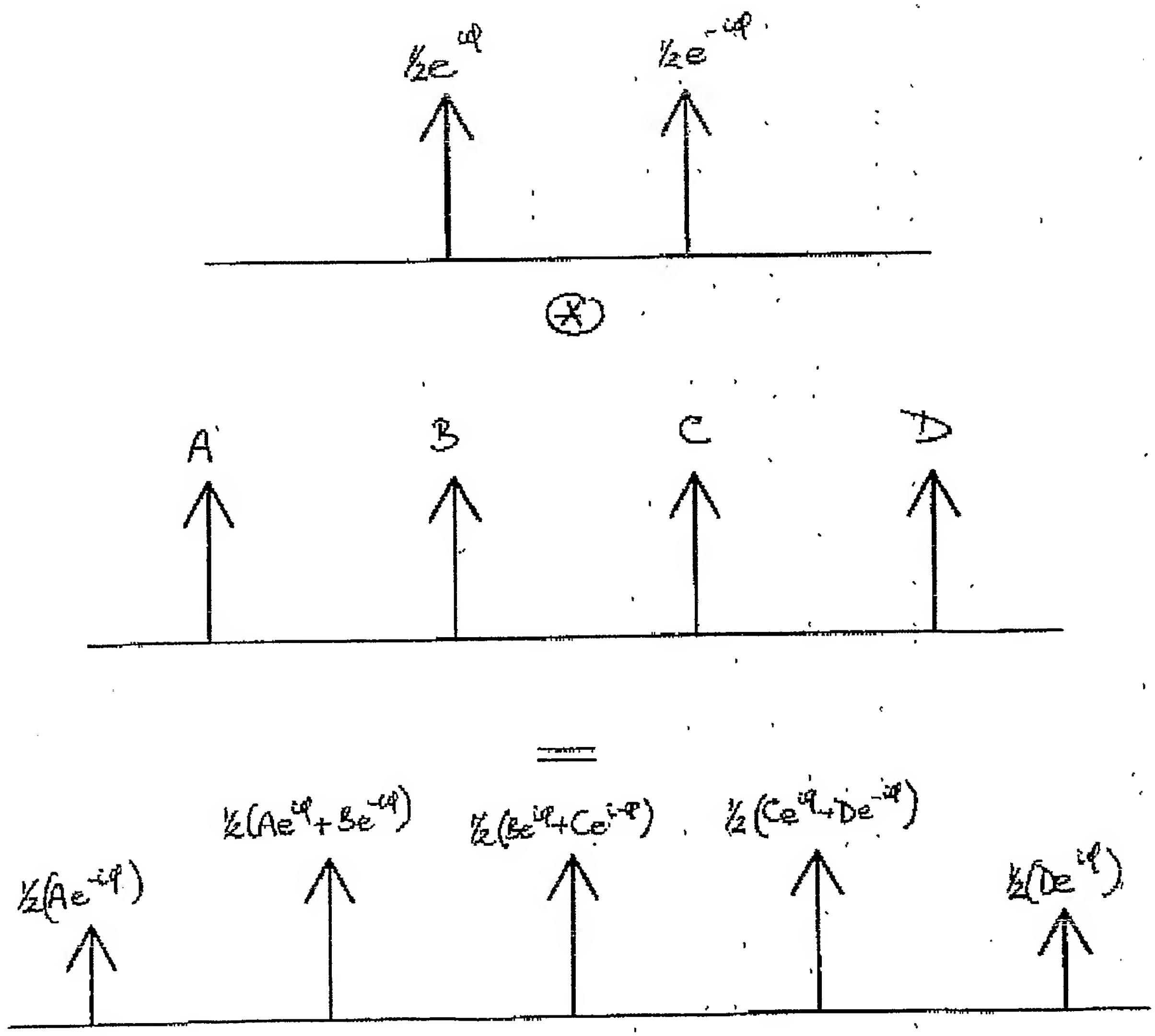

Fig 8

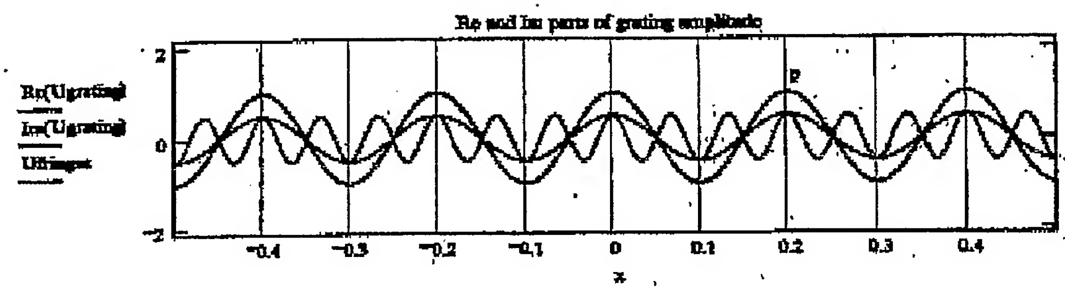

Fig 9a

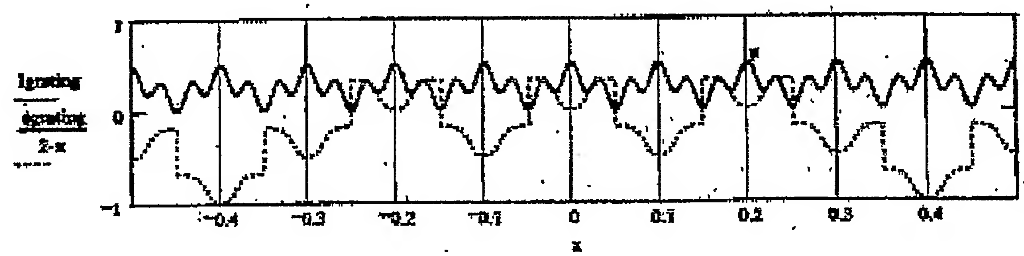

Fig 9b

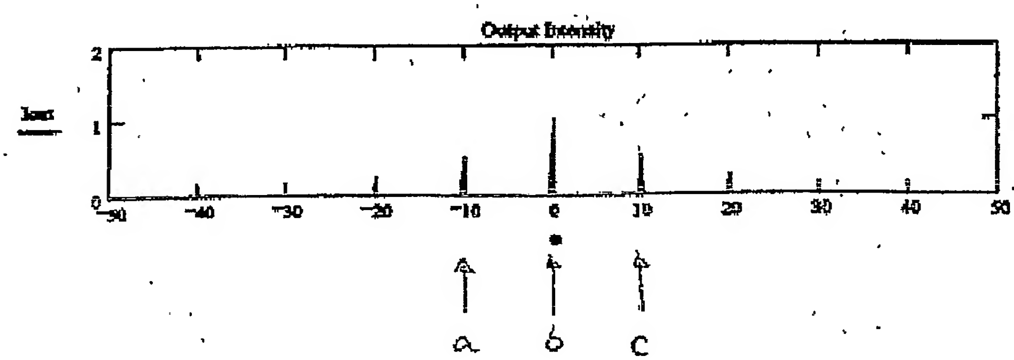

Fig 9c

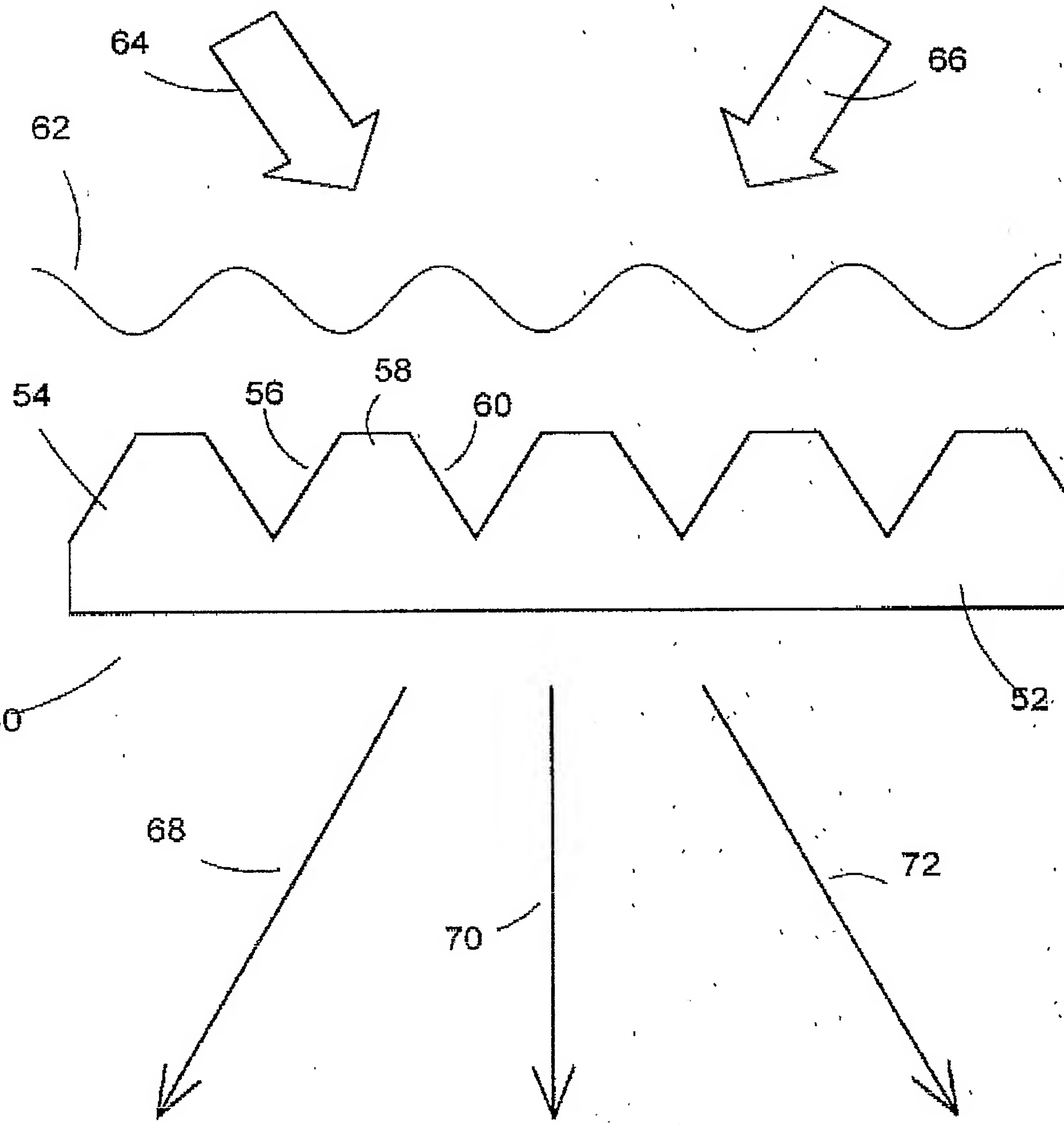

Fig 10

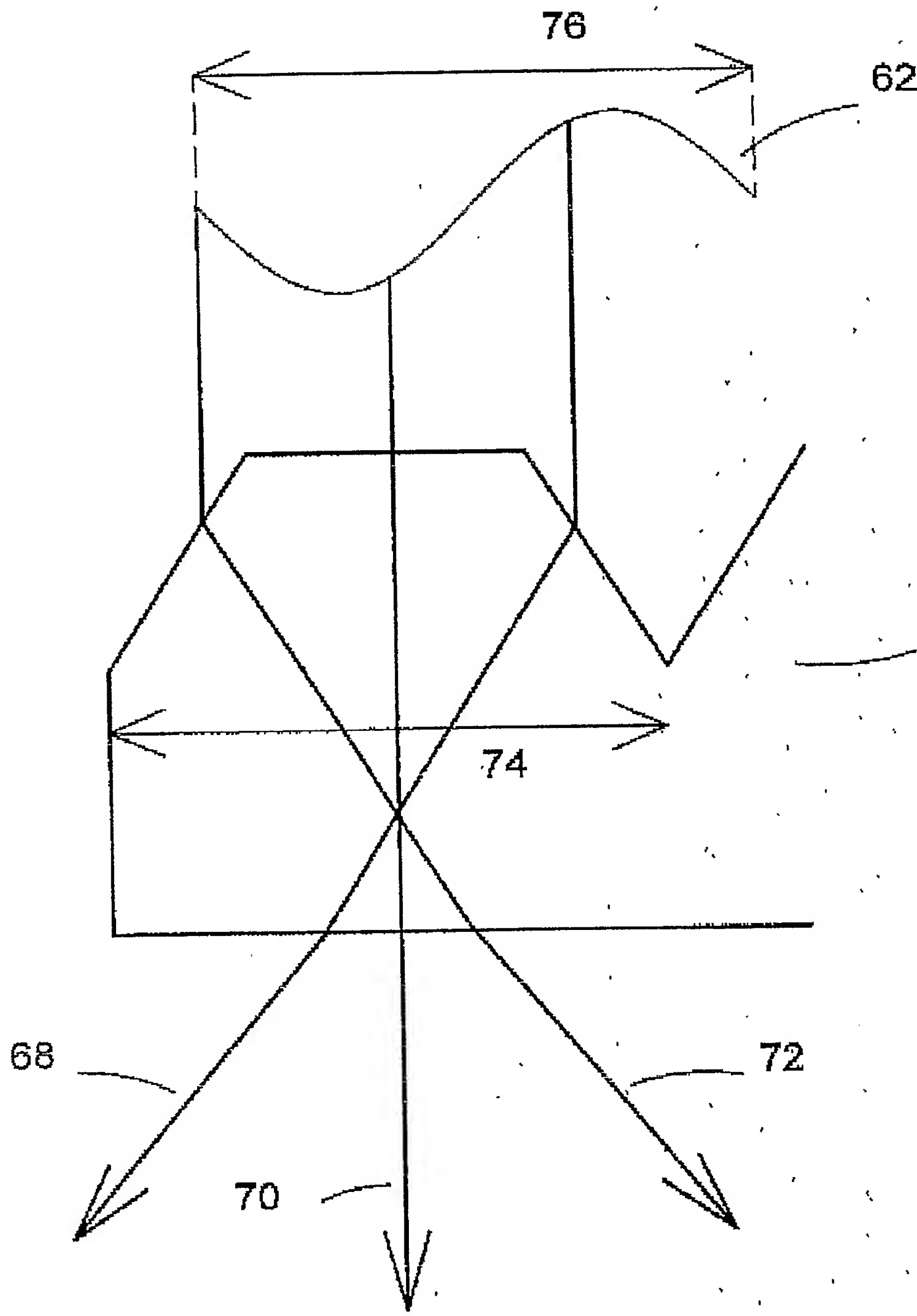

Fig 11

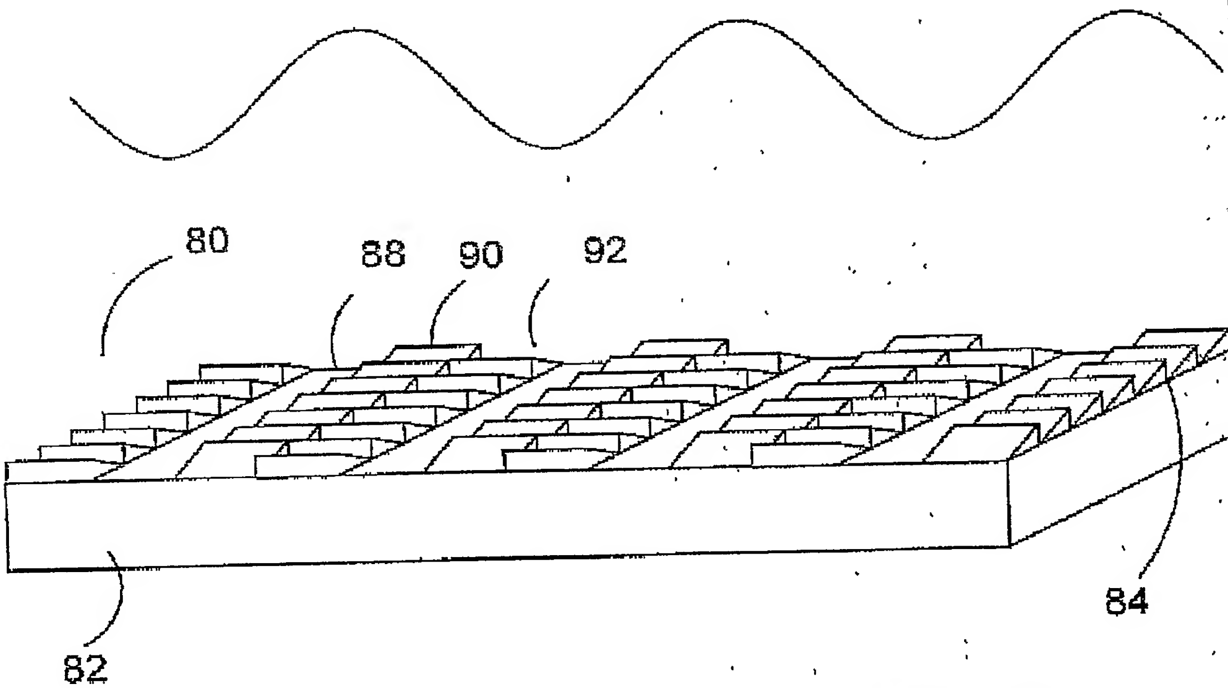

Fig 12

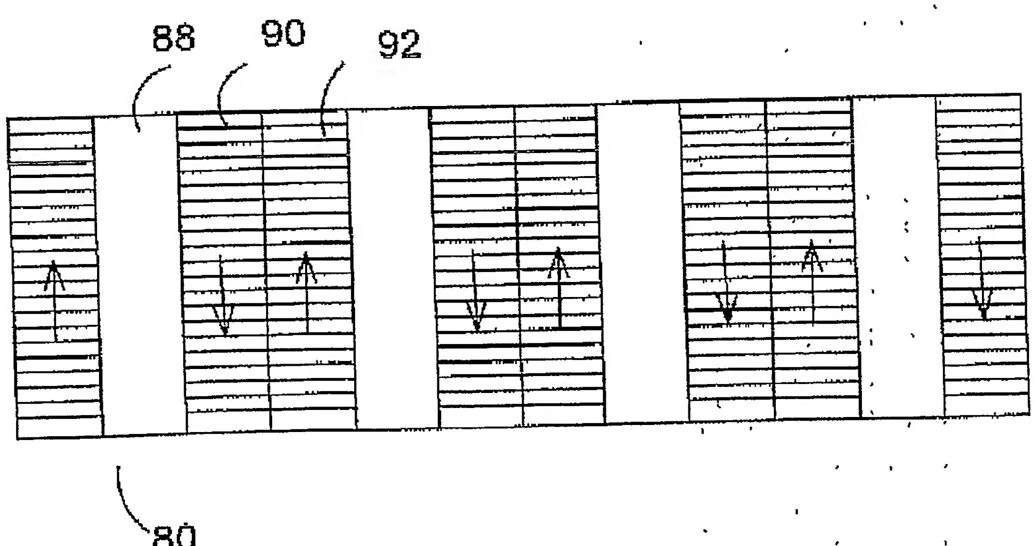

Fig 13

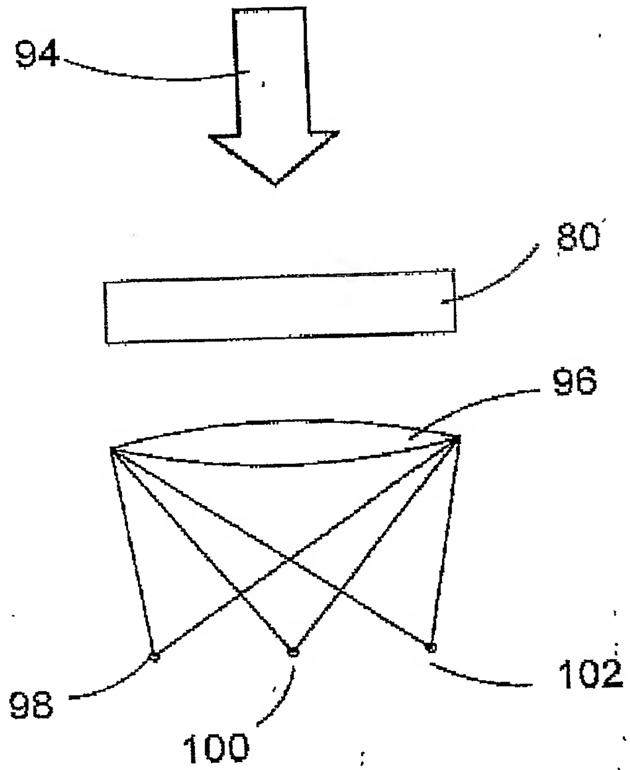

Fig 14

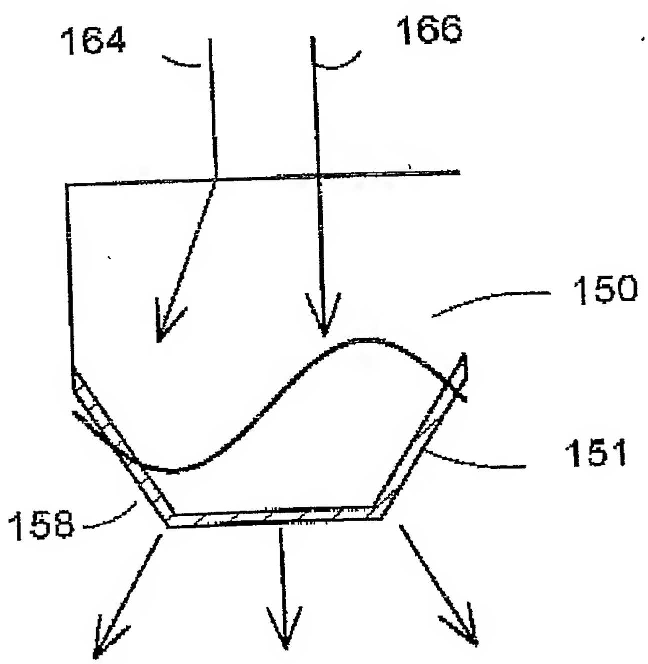

Fig 15

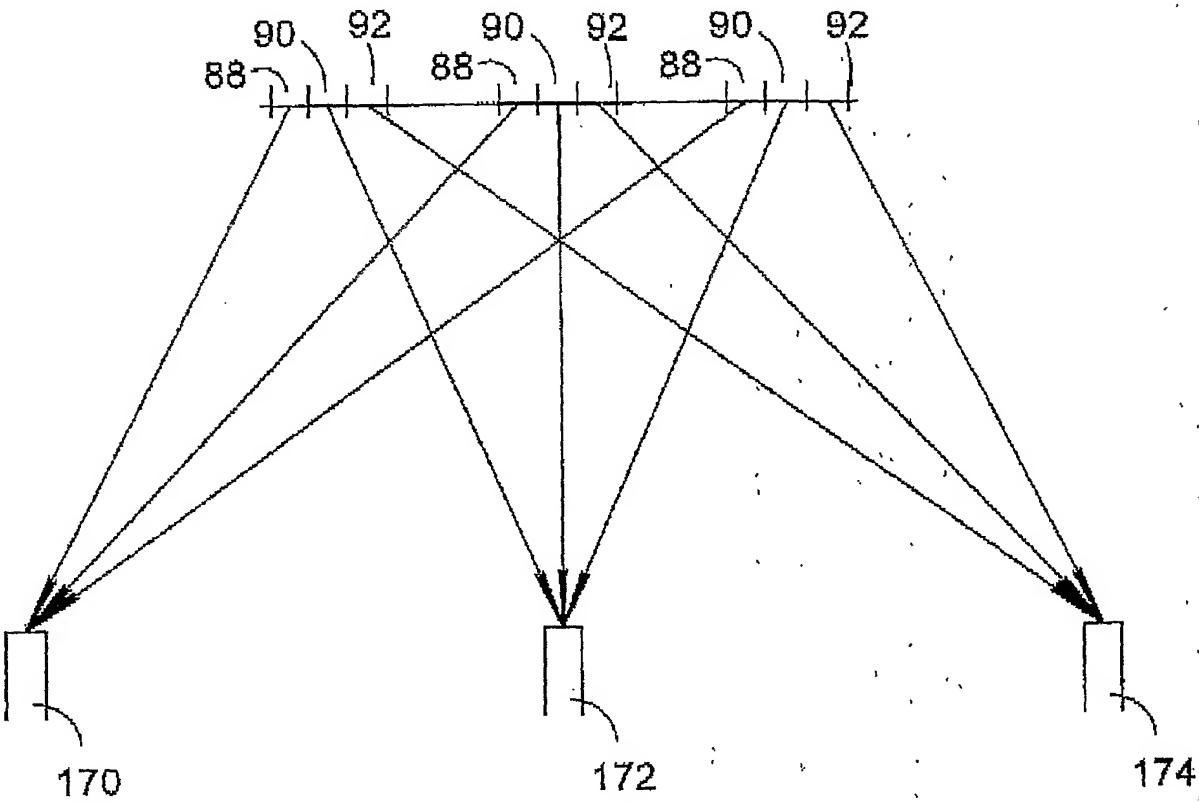

Fig 16

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